Constraints on Electron-quark Contact Interactions and Implications to models of leptoquarks and Extra Z Bosons

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We update the global constraint on four-fermion $eeqq$ contact interactions. In this update, we included the published data of H1 and ZEUS for the 94–96 run in the e^+p mode and the newly published data of H1 for the 1999 run in the e^-p mode. Other major changes are the new LEPII data on hadronic cross sections above 189 GeV, and the atomic parity violation measurement on Cesium because of a new and improved atomic calculation, which drives the data within 1σ of the standard model value. The global data do not show any evidence for contact interactions, and we obtain 95% C.L. limits on the compositeness scale. A limit of $\Lambda_{LL+(-)}^{eu} > 23\,(12.5)$ TeV is obtained. Implications to models of leptoquarks and extra Z bosons are examined.

I. INTRODUCTION

Four-fermion contact interaction is not something new, but was proposed decades ago by Fermi to account for the nuclear beta decay. The interaction is represented by

$$\mathcal{L} \sim G_F \left(\bar{e}\gamma^\mu(1-\gamma^5)\nu \right) \ \left(\bar{u}\gamma_\mu(1-\gamma^5)d \right)$$

where G_F is the Fermi constant with dimension [mass]$^{-2}$. This interaction is not renormalizable because the amplitude grows indefinitely with the energy scale if G_F is kept constant. It was only until 60's that the electroweak theory was proposed. The four-fermion contact interaction was then replaced by an exchange of the weak gauge boson W and G_F replaced by the W boson propagator: $G_F \to 1/(p^2 - m_W^2)$. The weak gauge bosons were only discovered later when the energy scale reached the hundred GeV level. In the above history we learn a couple of lessons: (i) the existence of four-fermion contact interactions is a signal of new physics beyond the existing standard theory, and (ii) the exact nature of new physics is unknown at the low energy scale. Only when the energy scale is high enough can the nature of new physics be probed.

Previous and present collider experiments have been searching for signs of four-fermion contact interactions, including experiments at the Tevatron, at HERA, at LEP, and at low-energy e-N and ν-N scattering experiments (for a summary see Refs. [1,2].) If deviations from the standard model (SM) were seen this would be a clear indication of new physics and would drive our resources towards where the new physics belongs.

A global analysis of the neutral-current (NC) $eeqq$ data was performed three years ago [1], [1] which was motivated by the HERA anomaly [4,5], in which H1 and ZEUS recorded a significant excess in NC deep-inelastic cross sections in the high-Q^2 region. The advantage of analyzing the $eeqq$ contact interactions is that they can show up in a number of channels, therefore we can use global NC data sets to put bounds on $eeqq$ contact interactions.

Since then the data collected by H1 and ZEUS in 1997 agreed well the SM. We performed updates in 1998 [6] based on their preliminary data. Since our previous fits, there have been some other changes in the data sets, which will likely affect the fit, and so we update the analysis in this note. The changes are summarized as follows. In 1999, both H1 and ZEUS published their final data [7,8] on NC deep-inelastic scattering in the e^+p mode, which show good agreement with the SM, except that ZEUS still has two high Q^2 events where only 0.2 is expected. H1 also published their new data in the 1999 run in e^-p mode [8]. Other major changes are the new LEPII data on hadronic cross sections at energies above 189 GeV [9], and the atomic parity violation (APV) measurement on Cesium [10] because of a new and improved atomic calculation [11], which drives the data within 1σ of the SM value [12]. Note that the hadronic cross sections given by the LEP Electroweak Working Group [9] showed a 2.5σ deviation above the SM predictions.

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[1]A model-independent analysis was previously done in Ref. [3] for studying new physics at HERA.

The purpose of this note is to update the analysis that examines the NC data sets from current accelerator experiments to see if there is any sign of contact interactions. If so it is a signal of new physics; if not we put limits on the compositeness scale Λ.

In the next section, we describe the formalism and followed by the descriptions of various data sets in Sec. III. We present the fits and limits in Sec. IV. In Sec. V and VI, we extend the analysis to models of leptoquarks and extra Z bosons, respectively. We conclude in Sec. VII.

II. PARAMETRIZATION

The conventional effective Lagrangian of $eeqq$ contact interactions has the form [13]

$$L_{NC} = \sum_q \Big[\eta_{LL}^{eq} \left(\overline{e_L}\gamma_\mu e_L \right) \left(\overline{q_L}\gamma^\mu q_L \right) + \eta_{RR}^{eq} \left(\overline{e_R}\gamma_\mu e_R \right) \left(\overline{q_R}\gamma^\mu q_R \right)$$
$$+ \eta_{LR}^{eq} \left(\overline{e_L}\gamma_\mu e_L \right) \left(\overline{q_R}\gamma^\mu q_R \right) + \eta_{RL}^{eq} \left(\overline{e_R}\gamma_\mu e_R \right) \left(\overline{q_L}\gamma^\mu q_L \right) \Big] , \tag{1}$$

where eight independent coefficients $\eta_{\alpha\beta}^{eu}$ and $\eta_{\alpha\beta}^{ed}$ have dimension $(\text{TeV})^{-2}$ and are conventionally expressed as $\eta_{\alpha\beta}^{eq} = \epsilon g^2/\Lambda_{eq}^2$, with a fixed $g^2 = 4\pi$. The sign factor $\epsilon = \pm 1$ allows for either constructive or destructive interference with the SM γ and Z exchange amplitudes and Λ_{eq} represents the mass scale of the exchanged new particles, with coupling strength $g^2/4\pi = 1$. A coupling of this order is expected in substructure models and Λ_{eq} is often called the "compositeness scale".

In models with $\text{SU}(2)_L$ symmetry, we expect some relations among the contact interaction coefficients. The particle content has the left-handed leptons and quarks in SU(2) doublets $L = (\nu_L, e_L)$ and $Q = (u_L, d_L)$, while the right-handed electrons and quarks in singlets. The most general $SU(2)_L \times U(1)$ invariant contact term Lagrangian is given by

$$\mathcal{L}_{SU(2)} = \eta_1 \left(\overline{L}\gamma^\mu L \right) \left(\overline{Q}\gamma_\mu Q \right) + \eta_2 \left(\overline{L}\gamma^\mu T^a L \right) \left(\overline{Q}\gamma_\mu T^a Q \right)$$
$$+ \eta_3 \left(\overline{L}\gamma^\mu L \right) \left(\overline{u_R}\gamma_\mu u_R \right) + \eta_4 \left(\overline{L}\gamma^\mu L \right) \left(\overline{d_R}\gamma_\mu d_R \right)$$
$$+ \eta_5 \left(\overline{e_R}\gamma^\mu e_R \right) \left(\overline{Q}\gamma_\mu Q \right) + \eta_6 \left(\overline{e_R}\gamma^\mu e_R \right) \left(\overline{u_R}\gamma_\mu u_R \right)$$
$$+ \eta_7 \left(\overline{e_R}\gamma^\mu e_R \right) \left(\overline{d_R}\gamma_\mu d_R \right) . \tag{2}$$

By expanding the η_5 term we have

$$\eta_{RL}^{eu} = \eta_5 = \eta_{RL}^{ed} . \tag{3}$$

In addition, the four neutrino and the lepton couplings are also related by SU(2):

$$\eta_{LL}^{\nu u} = \eta_{LL}^{ed} , \eta_{LL}^{\nu d} = \eta_{LL}^{eu} , \eta_{LR}^{\nu u} = \eta_{LR}^{eu} , \eta_{LR}^{\nu d} = \eta_{LR}^{ed} . \tag{4}$$

In our analysis, the relations of Eqs. (3) and (4) are only used when neutrino scattering data are included in the analysis. We shall state clearly when these SU(2) relations are used or not. This is because in some combinations of η's, at least one of the SU(2) relations cannot be held, then we are forced not to use the SU(2) symmetry.

Even though we expect that $SU(2)_L \times U(1)$ will be a symmetry of the renormalizable interactions which ultimately manifest themselves as the contact terms of Eq. (1), electroweak symmetry breaking may break the mass degeneracy of SU(2) multiplets of the heavy quanta that give rise to (1). This would result in a violation of the relations of Eqs. (3) and (4).

Because of severe experimental constraints on intergenerational transitions like $K \to \mu e$ we restrict our discussions to first generation contact terms. Only where required by particular data (e.g. the muon sample of Drell-yan production at the Tevatron) shall we assume universality of contact terms between e and μ.

Let us start with the scattering process $q\bar{q} \to \ell^+\ell^-$ ($\ell = e, \mu$). The amplitude squared for $q\bar{q} \to \ell^+\ell^-$ or $\ell^+\ell^- \to q\bar{q}$ (without averaging initial spins or colors) is given by

$$\sum |\mathcal{M}|^2 = 4u^2 \left(|M_{LL}^{\ell q}(s)|^2 + |M_{RR}^{\ell q}(s)|^2 \right) + 4t^2 \left(|M_{LR}^{\ell q}(s)|^2 + |M_{RL}^{\ell q}(s)|^2 \right) , \tag{5}$$

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where

$$M_{\alpha\beta}^{\ell q}(s) = \frac{e^2 Q_\ell Q_q}{s} + \frac{e^2 g_\alpha^\ell g_\beta^q}{\sin^2\theta_{\rm w}\cos^2\theta_{\rm w}} \frac{1}{s - M_Z^2} + \eta_{\alpha\beta}^{\ell q} , \tag{6}$$

where s, t, u are the usual Mandelstam variables. In the above equations, $g_L^f = T_{3f} - Q_f\sin^2\theta_{\rm w}$, $g_R^f = -Q_f\sin^2\theta_{\rm w}$, Q_f is the electric charge of the fermion f in units of proton charge. The SM amplitude can be recovered by setting η's to zero.

For a large class of new interactions the new physics contributions $\eta_{\alpha\beta}^{eq}$ vary slowly with q^2, effectively being constant at energies accessible to present experiments, e.g., if the mass of the exchange quanta is much heavier than the energy scale of the experiments. In this case the $\eta_{\alpha\beta}^{ff'}$ correspond to constant four-fermion contact interactions, and Eq. (6) relates the sensitivity to new physics of all experiments probing a given combination of external quarks and leptons, such as $ep \to eX$, $p\bar{p} \to e^+e^-X$, $e^+e^- \to$ hadrons and atomic physics parity violation experiments. Based on the formula in Eq. (6) the amplitude squared for the deep-inelastic scattering at HERA can be obtained by a simple interchange of the Mandelstam variables.

III. GLOBAL DATA

The global data used in this analysis have been described in Ref. [1]. Here we only describe those that have been updated since then. We have used the most recent CTEQ (v.5) parton distribution functions [14] wherever they are needed.

A. HERA data

ZEUS [7] and H1 [8] have published their results on the NC deep-inelastic scattering (DIS) at e^+p collision with $\sqrt{s} \approx 300$ GeV. The data sets of H1 and ZEUS are based on accumulated luminosities of 35.6 and 47.7 pb^{-1}, respectively. H1 [8] also published NC data for the most recent run of e^-p collision at $\sqrt{s} \approx 320$ GeV with an integrated luminosity of 16.4 pb^{-1}.

We used the double differential cross section $d^2\sigma/dxdQ^2$ given by the H1 [8] data and the single differential cross section $d\sigma/dQ^2$ given by ZEUS [7] data in our fits. At e^+p collision, the double differential cross section for NC DIS, including the effect of η's, is given by

$$\frac{d^2\sigma}{dxdQ^2}(e^+p \to e^+X) = \frac{1}{16\pi} \left\{ \sum_q f_q(x) \left[(1-y)^2(|M_{LL}^{eq}(t)|^2 + |M_{RR}^{eq}(t)|^2) + |M_{LR}^{eq}(t)|^2 + |M_{RL}^{eq}(t)|^2 \right] \right.$$
$$\left. + \sum_{\bar{q}} f_{\bar{q}}(x) \left[|M_{LL}^{eq}(t)|^2 + |M_{RR}^{eq}(t)|^2 + (1-y)^2(|M_{LR}^{eq}(t)|^2 + |M_{RL}^{eq}(t)|^2) \right] \right\} , \tag{7}$$

where $Q^2 = sxy$ is the square of the momentum-transfer and $f_{q/\bar{q}}(x)$ are parton distribution functions. The reduced amplitudes $M_{\alpha\beta}^{eq}$ are given by Eq. (6). The single differential cross section $d\sigma/dQ^2$ is obtained by integrating over x. The corresponding formulas for e^-p collision can be obtained from the above equation by interchanging $(LL \leftrightarrow LR, RR \leftrightarrow RL)$.

We normalize the tree-level SM cross section to the low Q^2 part of the data set by a scale factor C (C is very close to 1.) The cross section $\sigma^{\rm th}$ used in the minimization procedure is then given by

$$\sigma^{\rm th} = C\left(\sigma^{\rm SM} + \sigma^{\rm interf} + \sigma^{\rm cont}\right) \tag{8}$$

where $\sigma^{\rm interf}$ is the interference cross section between the SM and the contact interactions and $\sigma^{\rm cont}$ is the cross section due to contact interactions.

B. Drell-yan Production

Both CDF [15] and DØ [16] measured the differential cross section $d\sigma/dM_{\ell\ell}$ for Drell-Yan production, where $M_{\ell\ell}$ is the invariant mass of the lepton pair. While CDF analyzed data from both electron and muon samples, DØ analyzed only the electron sample.

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The differential cross section, including the contributions of contact interactions, is given by

$$\frac{d^2\sigma}{dM_{\ell\ell}dy} = K\frac{M_{\ell\ell}^3}{72\pi s} \sum_q f_q(x_1)f_{\bar{q}}(x_2) \left(|M_{LL}^{eq}(\hat{s})|^2 + |M_{LR}^{eq}(\hat{s})|^2 + |M_{RL}^{eq}(\hat{s})|^2 + |M_{RR}^{eq}(\hat{s})|^2\right) , \qquad (9)$$

where $M_{\alpha\beta}^{eq}$ is given by Eq. (6), $\hat{s} = M_{\ell\ell}^2$, $\sqrt{s}$ is the center-of-mass energy of the $p\bar{p}$ collision, $M_{\ell\ell}$ and y are, respectively, the invariant mass and the rapidity of the lepton pair, and $x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{s}}e^{\pm y}$, and y is numerically integrated. The QCD K-factor is given by $K = 1 + \frac{\alpha_s(\hat{s})}{2\pi}\frac{4}{3}(1 + \frac{4\pi^2}{3})$.

We scale our tree-level SM cross section by normalizing to the Z-peak cross section data. The cross section used in the minimization procedure is then given similarly by Eq. (8).

C. LEP

The LEP Electroweak Working Group (LEPEW) combined the data on $q\bar{q}$ production from the four LEP collaborations [9] for energies between 130 and 202 GeV. In our previous fits, we have data upto 183 GeV only. In the LEPEW report, they also noted that the hadronic cross section, on average, is about 2.5σ above the SM prediction. In fact, we see this effect in our fits.

In the report, both the experimental cross sections and predictions from the next-leading-order (NLO) cross sections are given [9]. Since the NLO calculation for contact interactions is not available, we do the calculation by first normalizing our tree-level results to the NLO cross sections given in the report and then multiplying this scale factor to the new cross sections that include the SM and the contact interactions.

At leading order in the electroweak interactions, the total hadronic cross section for $e^+e^- \to q\bar{q}$, summed over all flavors $q = u, d, s, c, b$, is given by

$$\sigma_{\text{had}} = K \sum_q \frac{s}{16\pi}\left[|M_{LL}^{eq}(s)|^2 + |M_{RR}^{eq}(s)|^2 + |M_{LR}^{eq}(s)|^2 + |M_{RL}^{eq}(s)|^2\right], \qquad (10)$$

where $K = 1 + \alpha_s/\pi + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3$ is the QCD K factor.

We found that some of the fits are dominated by these $e^+e^- \to q\bar{q}$ hadronic cross sections. If data at even higher energies > 202 GeV are available, the limits will increase. In our fits, we assumed a more conservative scenario that contact interactions only appear in eu and ed channels. Have we assumed the universalities of $eu = ec$ and $ed = es = eb$, the limits obtained would have been significantly higher.

D. Atomic Parity Violation

The APV is measured in terms of weak charge Q_W. The updated experimental value with an improved atomic calculation [10,11] is about 1.0σ larger than the SM prediction [12], namely, $\Delta Q_W \equiv Q_W(\text{Cs}) - Q_W^{\text{SM}}(\text{Cs}) = 0.44 \pm 0.44$. The contribution to ΔQ_W from the contact parameters is given by [17,1]

$$\Delta Q_W = (-11.4 \text{ TeV}^2)\left[-\eta_{LL}^{eu} + \eta_{RR}^{eu} - \eta_{LR}^{eu} + \eta_{RL}^{eu}\right] + (-12.8 \text{ TeV}^2)\left[-\eta_{LL}^{ed} + \eta_{RR}^{ed} - \eta_{LR}^{ed} + \eta_{RL}^{ed}\right] . \qquad (11)$$

Note that the η's come in special combinations. If for some specific combinations: e.g., vector-vector (VV): $\eta_{VV} = \eta_{LL} = \eta_{LR} = \eta_{RL} = \eta_{RR}$ and axial-vector-axial-vector (AA): $\eta_{AA} = \eta_{LL} = -\eta_{LR} = -\eta_{RL} = \eta_{RR}$, the contributions to ΔQ_W are zero.

There are also electron-nucleon scattering data, which have not been updated since our previous fits. The contributions to the asymmetries that were measured in these experiments are automatically zero for similar combinations of η's.

E. Charged-current (CC) Universality

The difference $\eta_{LL}^{ed} - \eta_{LL}^{eu} = \eta_2/2$ measures the exchange of isospin triplet quanta between left-handed leptons and quarks, as indicated by the presence of the $SU(2)$ generators $T^a = \sigma^a/2$ in the η_2 term. This term also provides an $e\nu ud$ contact term in CC processes. Such contributions, however, are severely restricted by lepton-hadron universality

of weak charged currents [18] within the experimental verification of unitarity of the CKM matrix. The experimental values [19]

$$|V_{ud}^{\text{exp}}| = 0.9735 \pm 0.0008 \ , \ |V_{us}^{\text{exp}}| = 0.2196 \pm 0.0023 \ , \ |V_{ub}^{\text{exp}}| = 0.0036 \pm 0.0010 \ , \tag{12}$$

lead to the constraint

$$\left(|V_{ud}^{\text{SM}}|^2 + |V_{us}^{\text{SM}}|^2 + |V_{ub}^{\text{SM}}|^2\right)\left(1 - \frac{\eta_2}{4\sqrt{2}G_F}\right)^2 = 0.9959 \pm 0.0019 \ , \tag{13}$$

when flavor universality of the contact interaction is assumed. As a result η_2 must be small, though not necessarily negligible,

$$\eta_2 \equiv 2(\eta_{LL}^{ed} - \eta_{LL}^{eu}) = (0.135 \pm 0.063) \text{ TeV}^{-2} \ . \tag{14}$$

Other data we used in our fits include low-energy electron-nucleon scattering experiments [20] and neutrino-nucleon scattering experiments [21]. When considering constraints from neutrino-nucleon scattering experiments, we invoke the $SU(2)$ relations and e–μ universality in order to restrict the number of free parameters. In addition to using the relations of Eqs. (3) and (4), we will also impose the CC constraint on η_2 when neutrino data are included in the fits.

IV. FITS AND LIMITS

The fits of contact parameters are obtained by minimizing the χ^2 of the data sets. In order to see how each data set affects the fit, we first show the fits with each data set added one at a time, as shown in Table I. We observe the following: (i) the SM model fits the data well with $\chi_{\text{SM}}^2/\text{d.o.f.} \lesssim 1$ for all five columns in Table I. (ii) The contact interaction fits the data slightly better than the SM. In the last column of Table I, the $\chi_{\text{SM}}^2/\text{d.o.f.} = 0.975$ while $\chi_{\text{cont}}^2/\text{d.o.f.} = 0.936$, where χ_{SM}^2 and χ_{cont}^2 are the chi-square for the SM and contact interactions, respectively. (iii) The χ_{cont}^2 for APV in all cases are zero, which means that the minimization procedure prefers the APV data to be satisfied. In other words, other choices of η's would give a too large χ^2 if APV data is violated to a large extent.

In view of these, we conclude that the global data do not show any sign of contact interactions. Thus, we can derive 95% C.L. limits on the compositeness scale, below which the contact interaction is ruled out. The 95% C.L. one-sided limits $\eta_{\pm}^{95}$ are defined, respectively, as

$$0.95 = \frac{\int_0^{\eta_+^{95}} d\eta \ P(\eta)}{\int_0^{\infty} d\eta \ P(\eta)} \qquad \text{and} \qquad 0.95 = \frac{\int_{\eta_-^{95}}^0 d\eta \ P(\eta)}{\int_{-\infty}^0 d\eta \ P(\eta)} \tag{15}$$

where $P(\eta)$ is the fit likelihood given by $P(\eta) = \exp(-(\chi^2(\eta) - \chi_{\text{min}}^2)/2)$. The 95% C.L. limits on $\Lambda_{\pm} = \sqrt{\pm\frac{4\pi}{\eta_{\pm}^{95}}}$. The limits on $\Lambda_{\pm}$ are summarized in Tables II–IV. In Table II, for each chirality coupling considered the others are put to zero. The limits on Λ obtained range from 10–26 TeV, which improve significantly from each individual experiment. We also calculate the limits on the compositeness scale when some symmetries on contact terms are considered, as shown in Table III: VV stands for vector-vector: $\eta_{LL} = \eta_{LR} = \eta_{RL} = \eta_{RR} = \eta_{VV}$, while AA stands for axial-vector-axial-vector: $\eta_{LL} = -\eta_{LR} = -\eta_{RL} = \eta_{RR} = \eta_{AA}$. These limits, in general, are not as strong as those in the previous table because the additional symmetry automatically satisfies the parity violation experiments: APV and e-N.

Finally, we show the limits that can be obtained from each set of data by looking at the results of LL and VV cases. The former is constrained severely by the APV and CC data, while the latter is free from the APV data. For the LL case the most dominant constraint is the CC universality, followed closely by the APV data (as indicated by the error of the best fit values.) The stringencies of the CC universality is understood because the LL interaction affects the $V - A$ structure. The CC universality will not constrain chirality combinations other than LL. On the other hand, parity-violating experiments will not be able to constrain the VV case, and the strongest constraint then comes from the LEP hadronic cross sections.

V. IMPLICATIONS TO LEPTOQUARK MODELS

The interaction Lagrangians for the $F = 0$ and $F = -2$ (F is the fermion number) scalar leptoquarks are [22]

$$\mathcal{L}_{F=0} = \lambda_L \overline{\ell_L} u_R \mathcal{S}_{1/2}^L + \lambda_R^* \overline{q_L} e_R (i\tau_2 \mathcal{S}_{1/2}^{R*}) + \tilde{\lambda}_L \overline{\ell_L} d_R \tilde{\mathcal{S}}_{1/2}^L + h.c. , \tag{16}$$

$$\mathcal{L}_{F=-2} = g_L \overline{q_L^{(c)}} i\tau_2 \ell_L \mathcal{S}_0^L + g_R \overline{u_R^{(c)}} e_R \mathcal{S}_0^R + \tilde{g}_R \overline{d_R^{(c)}} e_R \tilde{\mathcal{S}}_0^R + g_{3L} \overline{q_L^{(c)}} i\tau_2 \vec{\tau} \ell_L \cdot \vec{\mathcal{S}}_1^L + h.c. \tag{17}$$

where q_L, ℓ_L denote the left-handed quark and lepton doublets, u_R, d_R, e_R denote the right-handed up-type quark, down-type quark, and lepton singlet, and $q_L^{(c)}, u_R^{(c)}, d_R^{(c)}$ denote the charge-conjugated fields. The subscript on leptoquark fields denotes the weak-isospin of the leptoquark, while the superscript (L, R) denotes the handedness of the lepton that the leptoquark couples to. The color indices of the quarks and leptoquarks are suppressed. Note that the above Lagrangians have the $SU(2)_L$ symmetry and thus obey the SU(2) relations in Eqs. (3) and (4).

It is convenient to express the effects of leptoquarks in terms of the contact interaction coefficients η's. This is made possible when the mass of the leptoquark is much larger than the momentum transfer in the process. We classify the effects as follows.

(i) $\mathcal{S}_{1/2}^{L,R}$:

$$\eta_{LR}^{eu} = -\frac{|\lambda_L|^2}{2M_{\mathcal{S}_{1/2}}^2} = \eta_{LR}^{\nu u} ,$$

$$\eta_{RL}^{eu} = -\frac{|\lambda_R|^2}{2M_{\mathcal{S}_{1/2}}^2} = \eta_{RL}^{ed} . \tag{18}$$

(ii) $\tilde{\mathcal{S}}_{1/2}^L$:

$$\eta_{LR}^{ed} = -\frac{|\tilde{\lambda}_L|^2}{2M_{\tilde{\mathcal{S}}_{1/2}}^2} = \eta_{LR}^{\nu d} . \tag{19}$$

(iii) $\mathcal{S}_0^{L,R}$:

$$\eta_{LL}^{eu} = \frac{|g_L|^2}{2M_{\mathcal{S}_0}^2} = \eta_{LL}^{\nu d} ,$$

$$\eta_{RR}^{eu} = \frac{|g_R|^2}{2M_{\mathcal{S}_0}^2} . \tag{20}$$

(iv) $\tilde{\mathcal{S}}_0^R$:

$$\eta_{RR}^{ed} = \frac{|\tilde{g}_R|^2}{2M_{\tilde{\mathcal{S}}_0}^2} . \tag{21}$$

(v) $\vec{\mathcal{S}}_0^L$:

$$\eta_{LL}^{eu} = \frac{|g_{3L}|^2}{2M_{\vec{\mathcal{S}}_1}^2} = \eta_{LL}^{\nu d} ,$$

$$\eta_{LL}^{ed} = \eta_{LL}^{\nu u} = 2\eta_{LL}^{eu} . \tag{22}$$

Once we expressed the effects in terms of η's, we can directly analyze the combinations of η's in the global fit. The resulting limits are given in terms of $\lambda^2/2M_{LQ}^2$. Conventionally, the coupling constants $\lambda_{L,R}$ or $g_{L,R,3L}$ are assumed the electromagnetic strength, i.e., $\lambda_{L,R} = e = g_{L,R,3L}$ and thus we can obtain the lower limits on M_{LQ}. These results are summarized in Table V. Roughly, the leptoquark masses are required to be larger than 1 TeV, in order to satisfy all the constraints (except that $\mathcal{S}_0^{L,R}$ has to be heavier than 1.7 TeV and $\mathcal{S}_{1/2}^{L,R}$ can be as light as 0.67 TeV) when the coupling constants are assumed an electromagnetic strength e. The strongest constraint comes from APV and CC universality, the latter of which constrains the LL chirality severely.

This is an interesting result in view of the recent measurement of muon anomalous magnetic moment [23] with respect to a couple of leptoquark solutions [24]. The most favorable leptoquark solution to the muon anomaly is $\mathcal{S}_{1/2}^{L,R}$ that has both left- and right-handed couplings with the allowed mass range in 0.8 TeV $< M_{\mathcal{S}_{1/2}} <$ 2.2 TeV. This solution is in total consistency with the global NC constraint (as shown in (i) of Table V.)

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VI. IMPLICATIONS TO Z' MODELS

We can write down the Lagrangian of a generic Z' model coupling to fermions as

$$\mathcal{L} = -g_E \sum_f \bar{f} \gamma^\mu \left(\epsilon_L(f) \, P_L + \epsilon_R(f) P_R \right) f \, Z'_\mu \, , \tag{23}$$

where $P_{L,R} = (1 \mp \gamma^5)/2$, $g_E = \sqrt{5\lambda_g/3} \, e / \cos\theta_{\rm w}$ and λ_g is typically in the range $2/3 - 1$ and for grand-unified theories breaking directly into SU(3)×SU(2)×U(1)×U(1)' $\lambda_g = 1$, and $\epsilon_{L,R}(f)$ are the left- and right-handed chiral couplings to the Z'. Here in this simple analysis, we assume that the Z' does not mix with the SM Z boson such that the Z' is not constrained by the electroweak precision data [25].

The contribution of the Z' to the reduced amplitudes is given by

$$M_{\alpha\beta}^{eq} = M_{\alpha\beta}^{eq}\Big|_{\rm SM} + \frac{g_E^2}{q^2 - M_{Z'}^2} \, \epsilon_\alpha(e) \, \epsilon_\beta(q) \, . \tag{24}$$

In other words, if $M_{Z'}^2 \gg q^2$ the effects of Z' can be expressed in terms of the contact interaction parameters η's as

$$\eta_{\alpha\beta}^{eq} = -\frac{g_E^2}{M_{Z'}^2} \, \epsilon_\alpha(e) \, \epsilon_\beta(q) \, . \tag{25}$$

Once we expressed the effects of Z' in terms of contact interaction parameters, we can easily analyze the Z' models in our global fit. We shall analyze the following Z' models ($\lambda_g = 1$) [26]:
(i) Sequential Z model:

$$\epsilon_{L,R}(f) = T_{3f} - Q_f \sin^2\theta_{\rm w} \, . \tag{26}$$

(ii) Left-right Z_{LR} model:

$$\epsilon_L(f) = \sqrt{\frac{3}{5}} \left(\frac{-1}{2\alpha} \right) (B-L)_f \, , \quad \epsilon_R(f) = \sqrt{\frac{3}{5}} \left[\alpha T_{3R}^f - \frac{1}{2\alpha} (B-L)_f \right] \, , \quad \alpha = \sqrt{\frac{1 - 2\sin^2\theta_{\rm w}}{\sin^2\theta_{\rm w}}} \, . \tag{27}$$

(iii) Z_χ model:

$$\epsilon_L(u) = -\epsilon_R(u) = \epsilon_L(d) = \frac{\epsilon_R(d)}{3} = -\frac{\epsilon_L(e)}{3} = -\epsilon_R(e) = -\frac{\epsilon_L(\nu)}{3} = -\frac{1}{2\sqrt{10}} \, . \tag{28}$$

(iv) Z_ψ model:

$$\epsilon_L(u) = -\epsilon_R(u) = \epsilon_L(d) = -\epsilon_R(d) = \epsilon_L(e) = -\epsilon_R(e) = \epsilon_L(\nu) = \frac{1}{\sqrt{24}} \, . \tag{29}$$

(v) Z_η model:

$$\epsilon_L(u) = -\epsilon_R(u) = \epsilon_L(d) = 2\epsilon_R(d) = -2\epsilon_L(e) = -\epsilon_R(e) = -2\epsilon_L(\nu) = -\frac{2}{2\sqrt{15}} \, . \tag{30}$$

Note that the Z_ψ gives an axial-vector-axial-vector interaction, which evades strong constraints of APV and CC universality. In fact, Z_χ and Z_η are also not constrained by CC universality. The resulting best estimates of $g_E^2/M_{Z'}^2$ for each model are shown in Table VI, with the corresponding lower limits on Z' masses.

The results shown in the Table are not satisfactory. First, the lower mass limits on Z_ψ and Z_η are rather low, 0.16 and 0.43 TeV respectively. We have verified that Z_ψ gives only AA-type interactions and the result of Z_ψ is consistent with η_{AA}^{eq} of Table III. Such low mass values invalidate the assumption of Eq. (25), which means that we cannot apply the simple contact interaction analysis to these Z' models. In this case, more sophisticated q^2-dependent analysis is necessary to get an accurate result, which is beyond the scope of the present paper [2]. Nevertheless, it should be reasonably applicable to sequential Z model, Z_{LR} and Z_χ.

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[2]The CDF and DØ collaborations [27] have done such q^2-dependent analyses on Drell-yan production to put limits on Z' models.

VII. CONCLUSIONS

In conclusion, we have examined the NC *eeqq* data and found that the data do not support the existence of *eeqq* contact interactions with the compositeness scale upto 6–26 TeV, depending on the chiralities. We have also demonstrated that the low-energy data (APV and CC universality) dominate the fit for the LL chirality. In the case of parity-conserving contact interactions, the LEP hadronic cross section dominates the fit.

The above analysis has also been applied in a straight-forward fashion to other new physics such as leptoquark and Z' models. For leptoquark models we found the 95% C.L. lower mass limits range from 0.67 to 1.7 TeV. Especially, the leptoquark $\mathcal{S}_{1/2}^{L,R}$, which couples to both left- and right-handed charged leptons, has a mass limit of 0.67 TeV, which is consistent with the best leptoquark solution to the muon anomalous magnetic moment anomaly. For Z' models we found that our analysis is applicable to the sequential Z, Z_{LR}, and Z_χ models, with mass limits ranging from 0.68 to 1.5 TeV. We found that our analysis is not applicable to Z_ψ and Z_η models.

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TABLE I. The best estimate of the $\eta^{eq}_{\alpha\beta}$ parameters in units of TeV^{-2} when various data sets are added successively. In the last column when the ν-N data are included the $\eta^{\nu q}_{L\beta}$ are given in terms of $\eta^{eq}_{L\beta}$ by Eq. (4) and we assume $\eta^{eu}_{RL} = \eta^{ed}_{RL}$ in the last column.

	HERA only	HERA+APV +eN	HERA+APV +eN+DY	HERA+APV +eN+DY+LEP	HERA+DY+APV +eN+LEP+νN+CC
η^{eu}_{LL}	$-2.10\,^{+1.74}_{-1.76}$	$-1.74\,^{+1.14}_{-1.04}$	$0.09\,^{+0.39}_{-0.31}$	$0.07\,^{+0.37}_{-0.30}$	0.01 ± 0.20
η^{eu}_{LR}	$-2.49\,^{+1.49}_{-1.18}$	$-1.52\,^{+0.98}_{-1.12}$	$-0.16\,^{+0.40}_{-0.38}$	$-0.15\,^{+0.40}_{-0.38}$	$-0.21\,^{+0.22}_{-0.23}$
η^{eu}_{RL}	$-1.53\,^{+1.53}_{-1.38}$	$-2.47\,^{+1.11}_{-0.80}$	$-0.33\,^{+0.43}_{-0.39}$	$-0.32\,^{+0.42}_{-0.39}$	-0.22 ± 0.32
η^{eu}_{RR}	$-1.19\,^{+1.81}_{-1.83}$	$-1.37\,^{+0.98}_{-1.09}$	$-0.16\,^{+0.41}_{-0.36}$	$-0.19\,^{+0.38}_{-0.33}$	$-0.17\,^{+0.36}_{-0.26}$
η^{ed}_{LL}	$-5.35\,^{+2.88}_{-2.30}$	$-6.39\,^{+1.08}_{-0.92}$	$-0.21\,^{+0.88}_{-0.69}$	$-0.25\,^{+0.55}_{-0.52}$	0.08 ± 0.21
η^{ed}_{LR}	$-1.24\,^{+0.80}_{-0.79}$	$-1.48\,^{+0.77}_{-0.75}$	-0.93 ± 0.54	$-0.90\,^{+0.53}_{-0.51}$	$-0.62\,^{+0.34}_{-0.32}$
η^{ed}_{RL}	$-3.62\,^{+1.97}_{-1.30}$	$-2.41\,^{+1.56}_{-1.28}$	$-0.89\,^{+0.98}_{-0.76}$	$-0.78\,^{+0.91}_{-0.64}$	$= \eta^{eu}_{RL}$
η^{ed}_{RR}	$-6.01\,^{+3.18}_{-2.63}$	$-4.97\,^{+1.63}_{-1.51}$	$0.08\,^{+0.92}_{-0.90}$	$-0.02\,^{+0.47}_{-0.54}$	$-0.18\,^{+0.41}_{-0.48}$
HERA	230.4	231.3	250.9	250.8	251.3
APV		0.0	0.0	0.0	0.0
eN		0.6	0.7	0.7	1.4
DY			51.0	51.2	51.0
LEP				4.2	4.2
ν-N					0.1
Total χ^2 (χ^2_{cont})	230.4	232.0	302.6	306.9	307.9
SM χ^2 (χ^2_{SM})	257.4	260.3	311.1	321.7	327.7
SM d.o.f.	276	281	323	333	336

TABLE II. The best estimate on $\eta^{eq}_{\alpha\beta}$ and the 95% C.L. limits on the compositeness scale $\Lambda^{eq}_{\alpha\beta}$, where $\eta^{eq}_{\alpha\beta} = 4\pi\epsilon/(\Lambda^{eq}_{\alpha\beta\epsilon})^2$. When one of the η's is considered the others are set to zero. SU(2) relations are assumed and νN and CC data are included.

		95% C.L. Limits	
Chirality (q)	Best estimate (TeV^{-2})	Λ_+ (TeV)	Λ_- (TeV)
LL(u)	-0.044 ± 0.022	23.3	12.5
LR(u)	0.027 ± 0.038	11.6	14.8
RL(u)	-0.023 ± 0.018	23.1	15.2
RR(u)	-0.073 ± 0.037	17.9	9.7
LL(d)	0.065 ± 0.022	11.1	26.4
LR(d)	0.031 ± 0.034	11.7	15.9
RR(d)	-0.021 ± 0.034	15.2	12.3

TABLE III. The best estimate on η^{eq} for VV, AA, and the corresponding 95% C.L. limits on the compositeness scale Λ, where $\eta = 4\pi\epsilon/(\Lambda_\epsilon)^2$. When one of the η's is considered the others are set to zero. When we consider contact terms for just the u or d, we cannot apply SU(2) relations and so we do not include the νN and CC data. On the other hand, when both u and d contact terms are considered, we can apply the SU(2) relations and thus include the νN and CC data.

		95% C.L. Limits	
Chirality combinations	Best estimate (TeV^{-2})	Λ_+ (TeV)	Λ_- (TeV)
η^{eu}_{VV}	$-0.12\,^{+0.037}_{-0.036}$	20.0	8.4
η^{ed}_{VV}	$0.19\,^{+0.068}_{-0.072}$	6.6	12.2
η^{eu}_{AA}	$-0.15\,^{+0.054}_{-0.052}$	15.0	7.3
η^{ed}_{AA}	$0.18\,^{+0.055}_{-0.058}$	6.9	15.1
$\eta^{eu}_{VV} = \eta^{ed}_{VV}$	$-0.18\,^{+0.051}_{-0.048}$	15.7	7.0
$\eta^{eu}_{AA} = \eta^{ed}_{AA}$	$-0.20\,^{+0.15}_{-0.099}$	5.7	6.1

TABLE IV. The best estimate on η_{LL}^{eq} and η_{VV}^{eq} for each set of data as shown. The corresponding 95% C.L. lower limits on the compositeness scale Λ are also shown.

	HERA NC		Drell-yan		LEP σ_{had}		APV+eN+νN+CC	
	η (TeV^{-2})	Λ_+/Λ_- (TeV)	η	Λ_+/Λ_-	η	Λ_+/Λ_-	η	Λ_+/Λ_-
η_{LL}^{eu}	$-1.18\,^{+0.53}_{-0.56}$	5.3/2.4	$-0.19\,^{+0.24}_{-0.21}$	5.1/4.9	$-0.22\,^{+0.086}_{-0.084}$	12.3/5.9	-0.028 ± 0.023	20.6/13.7
η_{LL}^{ed}	$1.53\,^{+1.59}_{-1.35}$	1.6/2.9	$0.88\,^{+0.58}_{-0.73}$	2.7/2.7	$0.26\,^{+0.095}_{-0.098}$	5.6/11.4	0.054 ± 0.022	11.7/24.4
$\eta_{LL}^{eu}=\eta_{LL}^{ed}$	$-4.75\,^{+1.56}_{-1.13}$	4.7/1.4	$-0.19\,^{+0.32}_{-0.24}$	3.4/4.8	$-0.69\,^{+0.19}_{-0.16}$	3.0/3.7	0.017 ± 0.018	16.0/22.0
η_{VV}^{eu}	-0.30 ± 0.13	10.3/4.9	$-0.054\,^{+0.12}_{-0.11}$	6.7/7.4	$-0.11\,^{+0.042}_{-0.041}$	17.5/8.4	-	-
η_{VV}^{ed}	$-0.47\,^{+0.50}_{-0.48}$	4.1/3.2	$0.34\,^{+0.41}_{-1.27}$	3.7/3.0	$0.20\,^{+0.068}_{-0.072}$	6.5/2.4	-	-
$\eta_{VV}^{eu}=\eta_{VV}^{ed}$	$-0.38\,^{+0.14}_{-0.15}$	10.5/4.5	$-0.060\,^{+0.15}_{-0.11}$	5.0/7.2	$-0.19\,^{+0.068}_{-0.061}$	3.3/6.6	$-0.053\,^{+0.23}_{-0.27}$	5.8/1.9

TABLE V. The best estimate on the leptoquark parameter $\eta=\lambda^2/2M_{\text{LQ}}^2$, as well as the 95% C.L. upper limits on η. The corresponding 95% C.L. lower limits on the leptoquark mass are also shown, with the coupling constants $\lambda_{L,R}=g_{L,R,3L}=e$ assumed. The SU(2) relations are applied and νN and CC data are included in the global analysis.

	Best Estimate (TeV^{-2})	95% C.L. upper limits on η		95% C.L. lower limit on M_{LQ} (TeV)
		η_+^{95}	η_-^{95}	
(i) $\mathcal{S}_{1/2}^{L,R}$: $\eta_{LR}^{eu}=\eta_{RL}^{eu}$	-0.055 ± 0.033	0.038	-0.11	0.67
(ii) $\tilde{\mathcal{S}}_{1/2}^{L}$: η_{LR}^{ed}	0.031 ± 0.034	0.091	-0.050	1.0
(iii) $\mathcal{S}_0^{L,R}$: $\eta_{LL}^{eu}=\eta_{RR}^{eu}$	-0.087 ± 0.024	0.018	-0.13	1.7
(iv) $\tilde{\mathcal{S}}_0^{R}$: η_{RR}^{ed}	-0.021 ± 0.034	0.055	-0.083	0.94
(v) $\vec{\mathcal{S}}_0^{L}$: $\eta_{LL}^{eu}=\eta_{LL}^{ed}/2$	0.022 ± 0.011	0.040	-0.012	1.1

TABLE VI. The best estimate on the Z' model parameter $\eta=g_E^2/M_{Z'}^2$, as well as the 95% C.L. upper limits on η. The corresponding 95% C.L. lower limits on the Z' mass are also shown. The SU(2) relations are applied and νN and CC data are included in the global analysis. * in the table denotes that these values invalidate the assumption of Eq. (25) and thus not valid.

	Best Estimate (TeV^{-2})	95% C.L. upper limits on η		95% C.L. lower limit on $M_{Z'}$ (TeV)
		η_+^{95}	η_-^{95}	
(i) Sequential Z	-0.41 ± 0.12	0.095	-0.62	1.5
(ii) Z_{LR}	0.001 ± 0.15	0.29	-0.28	0.86
(iii) Z_χ	0.17 ± 0.17	0.46	-0.24	0.68
(iv) Z_ψ	$4.91\,^{+2.38}_{-3.65}$	8.18	-9.32	0.16^*
(v) Z_η	$-0.21\,^{+0.66}_{-0.67}$	1.16	-1.46	0.43^*